Design of Grass-Lined Open Channels

D. M. Temple
MEMBER
ASAE

This article is reprinted from the TRANSACTIONS of the ASAE (Vol. 26, No. 4, pp. 1064–1069, 1983)
Published by the American Society of Agricultural Engineers, St. Joseph, Michigan

ABSTRACT

TRACTIVE force design of grass-lined channels is discussed briefly in terms of its advantages and its limitations. A step by step computational procedure for stability design is presented with example computations and a discussion of the required parameters.

INTRODUCTION

Grass linings may provide an attractive alternative to structural stabilization methods for earth channels exposed to flow only intermittently. This form of protection has long been used for agricultural drainage channels. It is becoming increasingly popular for floodways and drainageways in more urban settings for both aesthetic and economic reasons.

The Soil Conservation Service's permissible velocity design procedure (SCS, 1954) has been the basis for virtually all grass-lined channel design since its initial introduction in 1947. This procedure is presented in graphical format and is based on data from extensive tests conducted by the U.S. Department of Agriculture (Ree and Palmer, 1949) and the Oklahoma Agricultural Experiment Station (Cox and Palmer, 1948). Graphical variations of the procedure have been devised to reduce the number of computations required for specific channel types (Normann, 1975; Garton and Green, 1981), but the approach is not well suited to programmed machine computations. It also suffers from the fact that permissible velocity is necessarily a function of channel geometry, slope, and soil type as well as vegetal properties.

Attempts to artificially simulate vegetal characteristics and behavior or to develop strictly analytic models of flow over grass have not yet been successful. Recent reanalysis of the available grass-lined channel data in terms of dominant parameters and tractive force concepts (Temple, 1980, 1982) has, however, provided the required relations for a numerical design approach which effectively separates vegetal, geometric, and soil parameters. The purpose of this report is to put these relations in the format of a computational procedure and to provide the background information necessary for its application. For convenience in applying the procedure, all of the required equations, tables, etc. are contained in the appendices. Equations are repeated in the text only as required for clarification of the discussion.

Article was submitted for publication in May, 1982; reviewed and approved for publication by the Soil and Water Division of ASAE in December, 1982. Presented as ASAE Paper No. 82-2066.

Cooperative research of the USDA-ARS, and the Oklahoma Agricultural Experiment Station, Stillwater, OK.

The author is: D. M. TEMPLE, Research Hydraulic Engineer, Hydraulic Engineering Research Unit, Crop Production and Water Conservation Laboratory, USDA-ARS, Stillwater, OK.

BASIS AND LIMITATIONS

Derivations of the relations presented in Appendix C and used in the tractive force design of vegetated channels are presented elsewhere (Temple, 1980, 1982) and will not be repeated here. In order to properly identify and understand the limitations of the procedure, however, it is necessary to briefly review the basic physical behavior involved.

The protective capability of a grass lining is seen to be the result of two separate, but related, actions. First, the presence of the vegetation results in a buffer region close to the boundary in which flow velocities are greatly reduced. This action is a direct result of the vegetal drag force being transmitted to the soil through the stem and root system. Because this region represents a distortion of the velocity profile, it is intimately related to flow resistance computations.

The second action of the grass is to prevent local and/or temporary high velocity and boundary stress regions associated with large scale turbulence or flow concentrations. Since this is a "weakest point" type of action, the degree of protection afforded is dominated by the uniformity of the cover at the soil boundary and is relatively independent of the flow resistance.

The effective tractive force approach accounts for these actions through adjustment of the total stress according to the relation (Temple, 1980):

$$\tau_e = \gamma DS(1 - C_F)(n_s/n)^2 \qquad [1]$$

where the variables are as defined in Appendix A. This relation, although appropriately dividing the protective actions of the grass, required approximating assumptions in its development as well as calibration of the vegetal cover factor (C_F) using observed permissible velocities. Its validity may, therefore, be limited to effective stresses on the order of those resulting in incipient channel failure. The relation does appear to be acceptable for a reasonably broad range of soil erodibility. This limitation is, therefore, not usually a consideration when applying equation [1] in the context of the stability design procedure (Appendix C, section 1).

Because the tractive force procedure represents a semiempirical dominant process model of flow behavior, there are computational limitations associated with the data base and with practical considerations which must be observed. These limitations are generally those previously placed on the permissible velocity procedure, although the parameter separation of the tractive force approach does provide a rational means of relaxing some of the data base restrictions when necessary.

In general terms, the procedure is limited to channels having a relatively uniform grass cover over a comparatively fine-grained soil. The soil surface should be free from discontinuities large enough to significantly influence total flow resistance. Also, the sediment available to the flow from sources other than the grass-lined boundary must be less than the transport capacity of the flow. Specific computational limits for the method may be summarized as:

$$B \geqslant B_{min} \quad \text{[L1]}$$

$$Z \geqslant Z_{min} \quad \text{[L2]}$$

$$0.0025\, C_I^{2.5} \leqslant R_V \leqslant 36 \quad \text{[L3]}$$

$$\tau_e \leqslant \tau_a \quad \text{[L4]}$$

where the variables are as defined in Appendix A.

Limiting relations [L1] and [L2] are a result of practical design considerations. They are included in the programmed computations to identify conditions where channel stability is not an appropriate criterion for the determination of channel geometry. These relations are also used to assure reasonable width to depth ratios as assumed by the use of maximum depth in equation [1]. Minimum values of bed width and/or side slope will depend on considerations such as construction techniques, slope stability, and the sunlight and moisture requirements of the cover.

Relation [L3] is a slightly modified form of the limits previously placed on the curve index approach to flow resistance. Using this approach, the discrete "n-VR curves" presented by the SCS (1954) are replaced by a curve family according to the relation (Temple, 1980):

$$n = \exp\left\{ C_I\,(0.0133[\ln(R_V)]^2 - 0.0954[\ln(R_V)] + 0.297) - 4.16 \right\} \quad [2]$$

where the variables are as defined in Appendix A.* Physically, the applicability of equation [2] is limited to conditions where the grass is submerged but continues to trail in the flow making the flow resistance a function of discharge or Reynold's number. Obviously, the mathematical limits specified by relation [L3] are inexact approximations of the desired physical conditions. Present analysis suggests that the lower limit should be more directly related to vegetal density. The present form, although considered acceptable for general application, may be overly conservative for dense stands of grass and too liberal for sparse stands. Since the interval specified by relation [L3] encloses the data base for equation [1], the two expressions are consistent.

Relation [L4] is a restatement of the basis for tractive force stability design. The relation states that the effective tractive force acting on the soil boundary must be less than the allowable tractive force for the soil.

*The form $y = \exp(x)$ implies $x = \ln(y) = \log_e(y)$.

PARAMETER ESTIMATION

The parameters used in equations [1] and [2] to describe the soil and cover conditions are the retardance curve index (C_I), the vegetal cover factor (C_F), the flow resistance associated with soil grain roughness (n_s), and the allowable effective tractive force (τ_a). Although each of these may be routinely estimated using the design aids contained in the appendices, a thorough understanding of the relation between these parameters and observable physical characteristics is desirable. Such an understanding allows the flexibility of the approach to be utilized through application of rational engineering judgment.

Retardance Curve Index

For submerged grasses, the curve index has been shown to relate to measurable physical characteristics as (Temple, 1982):

$$C_I = 2.5(h\sqrt{M})^{1/3} \quad [3]$$

where h and M are the stem length and density, respectively. Since C_I is used in the determination of flow resistance, average values of h and M are appropriate. Nonuniformity of height and density will become important only when it is sufficiently extensive to result in flow channelization.

Average stem length (h) may be estimated directly from a knowledge of local conditions and the growth characteristics of the grass selected. Because of its annual and seasonal variation, a realistic estimate for design purposes will usually result in an enveloping range rather than a single value. The conservative approach is, therefore, to assume the lower estimated value for stability considerations and the higher value in capacity calculations.

The stem density (M) expressed as the number of stems per unit area will show less seasonal variation than stem length, but may also be considered in terms of an enveloping range. This parameter, although simple in concept, will seldom be directly available. A guide for use in estimating stem density from grass type and quality of stands is included in Table 1 (Appendix B). Such an approach cannot, however, account for such factors as maintenance practices which tend to increase or decrease density. Rational adjustment of the tabulated values may be appropriate for specific design conditions.

Vegetal Cover Factor

Table 1 also serves as a guide for estimating the vegetal cover factor (C_F). This factor depends on a "weakest area" rather than on average conditions and appears to be dominated by uniformity of density. For stands of grass which may be described as reasonably dense and uniform the local uniformity of density is a direct function of grass type through growth characteristics. Table 1 depends on this relationship. Again, rational adjustment may be appropriate for specific conditions.

Soil Grain Roughness

The concept of soil grain roughness (n_s) has been discussed by numerous authors including Taylor and Brooks (1962). In brief and simplified form, it is the roughness associated with particles or aggregates of a size capable of being detached and transported by the flow. Data base limitations will generally limit the value of n_s to a constant of 0.0156 for grass-lined channel applications (Temple, 1980). This value implies a relatively fine-grained soil.

Allowable Effective Tractive Force

A guide for estimating the allowable effective tractive force for typical soils is presented as Table 2 (Appendix B). The values given are based on the permissible velocities given by Fortier and Scobey (1926). More data is needed to determine this parameter for a wider range of soil conditions. Experience with local soil conditions may justify modification of the tabulated values.

APPLICATION

The recommended computational procedure for stability design of grass-lined channels is presented in a step-by-step outline format as section 1 of Appendix C. The referenced equations are presented as section 2, and the procedure is illustrated by example in section 3. For brevity of presentation, the example computations are presented in SI units only. The procedure and its supporting equations are not unit system dependent as presented. The pertinent constant parameters in both SI and English units are summarized in Table 3 (Appendix B).

The numerical format of the recommended computational procedure makes it best suited to programed computation. Possible programing approaches range from separately programing key equations such as the allowable unit discharge relation (equation [8], Appendix C, section 2) for a hand held calculator, to the development of complete computer design routines. A routine offering flexible input, a selection of channel geometry, and automatic flagging of limit conditions was written as a check on the procedure outlined in Appendix C. The routine was written in BASIC language and was tested on the HP 9835A desktop computer.

SUMMARY

The computational procedure outlined in Appendix C places recent advances in the understanding of the behavior of flow over vegetation into the format of a numerical design procedure for grass-lined channels. The procedure is semiempirical and was formulated using a dominant parameter approach. It cannot, therefore, replace engineering judgment as an essential part of the design process. Limitations and weak points of the procedure have been identified. Modification, refinement, or replacement of the procedure may become appropriate with future advances in the understanding of the interaction between the flow and the vegetated boundary.

In addition to its numerical format, the advantages of the outlined procedure include reduced subjectivity in vegetal retardance estimation and increased flexibility in application. By separating the influence of the vegetal action from soil and geometry considerations, designs may be reasonably modified to reflect local conditions.

References

1. Cox, M. B., and V. J. Palmer. 1948. Results of tests on vegetated waterways, and methods of field application. Oklahoma Agric. Exp. Stn. Misc. Pub. No. MP-12. 43 p.
2. Fortier, S., and Scobey, F. C. 1926. Permissible canal velocities. Trans. ASCE 89:940-956.
3. Garton, J. E., and J. E. P. Green. 1981. Improved design procedures for vegetation-lined channels. Oklahoma Agric. Exp. Stn. Res. Rep. P-814, June 1981. 27 p.
4. Normann, J. M. 1975. Design of stable channels with flexible linings. Federal Highway Administration, Hydraulic Engineering Circular No. 15. 136 p.
5. Ree, W. O., and V. J. Palmer. 1949. Flow of water in channels protected by vegetative linings. USDA Tech. Bul. 967. 115 p.
6. Taylor, R. H., Jr., and N. H. Brooks. 1962. Discussion of "Resistance to flow in alluvial channels" by D. B. Simons and E. V. Richardson. Trans. ASCE 127 Part 1:982-992.
7. Temple, D. M. 1980. Tractive force design of vegetated channels. TRANSACTIONS of the ASAE 23(4):884-890.
8. Temple, D. M. 1982. Flow retardance of submerged grass channel linings. TRANSACTIONS of the ASAE 25(5):1300-1303.
9. USDA, Soil Cons. Service. 1947. (Revised 1954). Handbook of channel design for soil and water conservation. SCS-TP-61. 34 p.

APPENDIX A—VARIABLE DEFINITIONS

Variable	Definition	Dimensions
A	Channel cross sectional area	L^2
a	Locally defined coefficient	
a_c	Parabolic cross section coefficient ($Y = a_c X^2$)	L^{-1}
a_u	Unit dependent constant of Manning's equation	$L^{1/3}T^{-1}$
B	Bed width of a trapezoidal channel	L
B_{min}	Minimum acceptable bed width of a trapezoidal channel	L
b	Locally defined coefficient	
C_F	Vegetal cover factor	
C_I	Vegetal retardance curve index	
c	Locally defined coefficient	
D	Flow depth	L
h	Average stem length of a grass lining	L
M	Average number of stems per unit area	L^{-2}
n	Manning's coefficient for the entire channel	
n_s	Manning's coefficient associated with the soil only	
P	Channel wetted perimeter	L
Q	Volumetric channel discharge	L^3T^{-1}
q	Volumetric discharge per unit width of wide channel	L^2T^{-1}
R	Channel hydraulic radius	L
R_v	Form of flow Reynold's number assuming a reference viscosity (see equation [4])	
S	Energy slope	
V	Mean velocity (*i* subscript implies i^{th} iteration approximation)	L T^{-1}
V_m	Mean velocity computed by Manning's equation	L T^{-1}
W	Reference channel width (measured at ½ wide channel reference depth)	L
Z	Cotangent of bank slope angle (measured at water surface)	
Z_{min}	Minimum acceptable value of Z (based on soil and/or vegetal properties)	
γ	Unit weight of water	$ML^{-2}T^{-2}$
ν_{74}	Reference kinematic viscosity	L^2T^{-1}
τ_a	Allowable effective tractive force	$ML^{-1}T^{-2}$
τ_e	Effective tractive force	$ML^{-1}T^{-2}$

APPENDIX B—TABLES

TABLE 1. PROPERTIES OF GRASS CHANNEL LININGS
(Values apply to good uniform stands of each cover*)

Cover group	Estimated cover factor, C_F	Covers tested	Reference stem density	
			Stems/ft²	Stems/m²
Creeping grasses	0.90	Bermudagrass	500	5380
		Centipedegrass	500	5380
Sod forming grasses	0.87	Buffalograss	400	4300
		Kentucky bluegrass	350	3770
		Blue grama	350	3770
Bunch grasses	0.5	Weeping lovegrass	350	3770
		Yellow bluestem	250	2690
Legumes†	0.5	Alfalfa	500	5380
		Lespedeza sericea	300	3230
Annuals	0.5	Common lespedeza	150	1610
		Sudangrass	50	538

*Multiply the stem densities given by 1/3, 2/3, 1, 4/3, and 5/3, for 'poor, fair, good, very good, and excellent' covers, respectively. The equivalent adjustment to C_F remains a matter of engineering judgment until more data is obtained or a more analytic model is developed.
†For the legumes tested, the effective stem count for resistance (given) is approximately 5 times the actual stem count very close to the bed. Similar adjustment may be needed for other unusually large-stemmed and/or woody vegetation.

TABLE 2. ALLOWABLE EFFECTIVE TRACTIVE FORCE
Computed from Fortier and Scobey (1926) permissible velocities

Original material excavated	Allowable effective tractive force	
	lb/ft²	Pa
Sandy loam	0.0167	0.79
Silt loam	0.0218	1.04
Alluvial silts	0.0218	1.04
Ordinary firm loam	0.0341	1.63

TABLE 3. SUMMARY OF CONSTANTS*

Variable	Value	
	English units	SI units
a_u	1.49 $ft^{1/3}/s$	100 $m^{1/3}/s$
n_s	0.0156	0.0156
γ	62.4 lb/ft^3	9800 Nt/m^3
$\nu_{74} \times 10^5$	1.00 ft^2/s	0.0929 m^2/s
$3/7 \ln[\frac{a_u \times 10^{-5}}{\nu_{74}\gamma^{5/3} n_s^{10/3}}] - 4.16$	-1.00	-3.763

*Values are intended to apply to conditions normally encountered in the design of grass lined channels in fine grained materials.

APPENDIX C—COMPUTATIONAL PROCEDURE

SECTION 1: COMPUTATIONAL GUIDE FOR GRASS LINED CHANNEL DESIGN

I. Design for stability (Establishes control geometry)

A. Parameter estimation

1. Determine soil and cover conditions critical to stability
2. Estimate stem count (Table 1)
3. Estimate vegetal cover factor (Table 1)
4. Estimate allowable effective tractive force (Table 2)
5. Estimate retardance curve index (eq. [3])

B. Wide channel approximation (R = D)

1. Compute allowable unit discharge (eq. [8])
2. Compute R_v (eq. [9])
3. Compute Manning's n (eq. [2])
4. Compute flow depth (eq. [10])
5. Compute mean velocity (eq. [11])
6. Compute width required for total discharge (eq. [12])

C. Iterative solution

1. Use of the reference values of width and depth from part B to estimate the appropriate geometric control parameter (equations assume reference width at ½ reference depth) (eq. [G1__])
2. Use the velocity computed in part B as a first estimate
3. Compute required cross section area (eq. [6])
4. Compute required depth (eq. [G2__])
5. Compute wetted perimeter (eq. [G3__])
6. Compute hydraulic radius (eq. [7])
7. Compute R_v (eq. [4])
8. Compute Manning's n (eq. [2])
9. Compute velocity V_m (eq. [5])
10. Adjust velocity estimate (eq. [13])
11. Return to step 4 if desired convergence has not been reached
12. Compute effective tractive force (if unacceptable, adjust width and return to step 3) (eq. [1])
13. Check to assure conditions are within acceptable limits (eq. [L__])

II. Design for capacity (Establishes minimum channel depth)

A. Parameter estimation

1. Determine cover conditions governing capacity
2. Estimate stem count if different from part I (Table 1)
3. Estimate retardance curve index (eq. [3])

B. First iteration approximation

1. Assume P_v remains unchanged from part I
2. Compute first estimate of Manning's n (eq. [2])
3. Compute first estimate of hydraulic radius (eq. [14])
4. Compute first estimate of velocity (eq. [15])

C. Iterative solution

1. Compute required cross section area (eq. [6])
2. Compute required depth (eq. [G2__])

3. Compute wetted perimeter (eq. [G3__])
4. Compute hydraulic radius (eq. [7])
5. Compute R_ν (eq. [4])
6. Compute Manning's n (eq. [2])
7. Compute velocity V_m (eq. [5])
8. Adjust velocity estimate (eq. [13])
9. Return to step 2 if desired convergence has not been reached
10. Check to assure conditions are within acceptable limits (eq. [L__])

SECTION 2: SUMMARY OF EQUATIONS FOR GRASS-LINED CHANNELS

Flow Relations

Basic equations

$$\tau_e = \gamma DS(1 - C_F)(n_s/n)^2 \qquad [1]$$

$$n = \exp\left\{C_I\,(0.0133[\ln(R_V)]^2 - 0.0954[\ln(R_V)] + 0.297) - 4.16\right\} \qquad [2]$$

$$C_I = 2.5(h\sqrt{M})^{1/3} \qquad [3]$$

$$R_V = \frac{VR}{\nu_{74}} \times 10^{-5} \qquad [4]$$

$$V = \frac{a_u}{n} R^{2/3} S^{1/2} \qquad [5]$$

$$A = Q/V \qquad [6]$$

$$R = A/P \qquad [7]$$

Wide channel forms (R = D)

$$q = \nu_{74} \times 10^5 \exp\left(\frac{-b - \sqrt{b^2 - 4ac}}{2a}\right) \qquad [8]$$

where:

$$a = 0.0133\, C_I$$

$$b = -(0.0954\, C_I + 3/7)$$

$$c = 0.297\, C_I - 1/2\ln(S) + 5/7\ln\left(\frac{\tau_e}{1 - C_F}\right) + 3/7\ln\left(\frac{a_u \times 10^{-5}}{\nu_{74}\gamma^{5/3} n_s^{10/3}}\right) - 4.16$$

$$R_V = \frac{q}{\nu_{74} \times 10^5} \qquad [9]$$

$$D = \left(\frac{qn}{a_u S^{1/2}}\right)^{3/5} \qquad [10]$$

$$q = VD \qquad [11]$$

Approximating relation (from 'wide channel' to 'real channel')

$$W = Q/q \qquad [12]$$

Iterative velocity adjustment

$$V_{i+1} = V_i + 2/3(V_{m_i} - V_i) \qquad [13]$$

First iteration approximation (capacity computations)

$$R = \left(\frac{n\, R_V\, \nu_{74} \times 10^5}{a_u S^{1/2}}\right)^{3/5} \qquad [14]$$

$$V = \frac{R_V\, \nu_{74} \times 10^5}{R} \qquad [15]$$

Geometric Relations for principal channel types

Trapezoidal channels

$$B = W - ZD \qquad [G1a]$$

$$D = \frac{-B + \sqrt{B^2 + 4AZ}}{2Z} \qquad [G2a]$$

$$P = B + 2D\sqrt{Z^2 + 1} \qquad [G3a]$$

Triangular channels

$$Z = W/D \qquad [G1b]$$

$$D = \sqrt{A/Z} \qquad [G2b]$$

$$P = 2D\sqrt{Z^2 + 1} \qquad [G3b]$$

Parabolic channels

$$a_c = 2D/W^2 \qquad [G1c]$$

$$D = \left(3/4\, A\sqrt{a_c}\right)^{2/3} \qquad [G2c]$$

$$P = 2\left[\sqrt{D^2 + aD} + a\ln\left(\frac{\sqrt{D} + \sqrt{D + a}}{\sqrt{a}}\right)\right] \qquad [G3c]$$

where:

$$a = \frac{1}{4a_c}$$

Parabolic channels (useful forms for side-slope limited condition)

$$D = \sqrt{\frac{3A}{8Z}} \qquad [G2d]$$

$$P = D\left[\sqrt{Z^2+1} + Z^2 \ln\left(\frac{1+\sqrt{Z^2+1}}{Z}\right)\right] \quad \text{[G3d]}$$

Limiting relations

$$B \geqslant B_{min} \quad \text{[L1]}$$

$$Z \geqslant Z_{min} \quad \text{[L2]}$$

$$0.0025\, C_I^{2.5} \leqslant R_v \leqslant 36 \quad \text{[L3]}$$

$$\tau_e \leqslant \tau_a \quad \text{[L4]}$$

SECTION 3: EXAMPLE COMPUTATIONS

Problem Statement: Determine the width and depth required for a bermudagrass-lined channel in a silt loam soil. Channel is to be trapezoidal with side slopes of 2:1 and a bed slope of 3%. The design discharge is 10 m^3/s. Cover conditions are anticipated to range from a fair stand of grass with a stem length of 10 cm to a very good stand with a stem length of 40 cm.

Solution: The needed stability design parameters are estimated from the given information as:

$h = 0.100$ m

$M = 3600$ stems/m^2 . . . . (Table 1)

$C_F = 0.90$ . . . . (Table 1)

$\tau_e = 1.04$ Pa . . . . (Table 2)

from which:

$C_I = 4.54$ . . . . [3]

Under the assumption of a wide channel:

$q = 0.338\ m^3/s/m$ . . . . [8]

$R_v = 3.64$ . . . . [9]

$n = 0.0380$ . . . . [2]

$D = 0.210$ m . . . . [10]

$V = 1.6$ m/s . . . . [11]

Note that neither the total discharge or channel shape have entered the computations to this point. Comparisons of various soil and/or cover conditions may be made under the wide channel assumption without the need for iterative solutions.

The reference width is estimated to be:

$W = 29.6$ m . . . . [12]

Assuming W to be the width of the trapezoidal channel at a depth of D/2 results in a bed width of:

$B = 29.2$ m . . . . [G1a]

With the flow depth specified, computation of the flow depth or mean velocity is an iterative procedure.† Using mean velocity as the estimated variable in this procedure results in:

Variable — I	V	A	D	P	R	R_v	n	V_m
Units —	m/s	m^2	m	m	m	—	—	m/s
Ref. Eq. —	13	6	G2a	G3a	7	4	2	5
1	1.61	6.21	0.210	30.1	0.206	3.57	0.0382	1.58
2	1.59	6.29	0.212	30.1	0.209	3.57	0.0382	1.60

The effective tractive force is found to be:

$\tau_e = 1.04$ Pa . . . . [1]

which is equal to the allowable and, therefore, acceptable. R_v is also well within acceptable limits. This establishes the minimum value for the bed width as 29.2 m.

Vegetal parameter estimation for conditions governing capacity gives:

$h = 0.400$ m

$M = 7200$ stems/m^2 . . . . (Table 1)

from which:

$C_I = 8.09$ . . . . [3]

Assuming the reference Reynold's No. to remain unchanged ($R_v = 3.57$):

$n = 0.0769$ . . . . [2]

$R = 0.317$ m . . . . [14]

$V = 1.05$ m/s. . . . . [15]

Using this value of mean velocity as the starting point, the iterative solution is:

Variable — I	V	A	D	P	R	R_v	n	Vm
Units —	m/s	m^2	m	m	m	—	—	m/s
Ref. Eq. —	13	6	G2a	G3a	7	4	2	5
1	1.05	9.52	0.319	30.6	0.311	3.51	0.0776	1.02
2	1.03	9.71	0.325	30.7	0.316	3.50	0.0777	1.03

Again the limits are satisfied. The required relations are, therefore, a minimum bed width of 29.2 m and a minimum depth of 0.325 m plus freeboard.

†The iterative computations are recognized as an unnecessary refinement for a channel with this large a width to depth ratio. They are included here for illustration purposes. Small width to depth ratios will usually require more iterations.